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# The radiation characteristics of leaky coaxial cables at VHF

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## Summary

*Some experiments have been carried out to investigate the characteristics of a certain type of leaky coaxial cable. The theoretical background of radiation from such a cable is given and from the experimental results the suitability of this type of cable for broadcasting VHF purposes in the open is discussed.*

Issued under the authority of

P. Rainger

Head of Research Department

**Research Department, Engineering Division,**
**BRITISH BROADCASTING CORPORATION**
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# THE RADIATION CHARACTERISTICS OF LEAKY COAXIAL CABLES AT VHF

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# THE RADIATION CHARACTERISTICS OF LEAKY COAXIAL CABLES AT VHF

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## 1. Introduction

A system for radio communications in coal mines has been proposed which uses a leaky coaxial cable laid longitudinally down the length of a shaft to act as a transmitting aerial. Environmental difficulties make most other conventional communication systems impractical. The National Coal Board's Mining Research and Development Establishment has conducted an investigation into the feasibility of such a system. On present information, the system seems likely to be adopted by the Coal Board in some places.

This report describes work that was carried out to investigate the properties of leaky coaxial cables and to assess whether they could be used for broadcasting purposes. The main application envisaged is for small service areas where the topography makes conventional systems impractical; for example, a narrow valley containing a sharp bend.

The construction of the cable which was used in the experiments, is shown in Fig. 1. The braid of the cable is incomplete, allowing the coaxial fields within the cable to leak through and couple power to an external receiver. The rate of attenuation of the signal within the cable determines, to a large extent, the longitudinal range that can be covered by the system. The coupling between the signal inside the cable and an external receiver determines the power that has to be injected at the input of the cable. To determine the coupling loss of the cable, the field strength pattern of a 200 metre elevated length was measured in the frequency range 40 – 200 MHz. At higher frequencies the loss is excessive.

## 2. Theoretical background

The screening efficiency of a braided outer conductor coaxial cable is normally determined by measuring its surface transfer impedance,[1] defined as the ratio of the longitudinal electric field, on the outside of the braid to the current flowing inside the cable. Various standard methods[2] exist for measuring this parameter which is found to depend only on the braid construction and to be independent of the internal construction of the cable. For all these methods of measurement the sample of cable used must be short compared with the wavelength. The surface transfer impedance is dependent upon the disposition of the wire helices, and on the numbers and diameter of these wires. As would be expected it tends towards the d.c. resistance per unit length of the braid at low frequencies, but it increases in proportion to the frequency above a few megahertz.

It has been shown experimentally, that for lengths of cable very much greater than the signal wavelength, the current flowing on the outside of the braid is dependent not only on the surface transfer impedance but also to a large extent on the velocity ratio of the cable in the coaxial mode. A theory has been developed to explain the result[3] which assumes that the current induced by a small element of the coaxial cable on the outside of the braid propagates along the cable. In this case, the outside of the braid may be regarded as a single-wire transmission line or as a guiding structure for a surface wave. By making standing wave measurements on the outside of the cable the velocity of propagation and attenuation coefficient for the surface wave may be determined. The theory gives close agreement with experiment and a brief description of it is given in the Appendix.

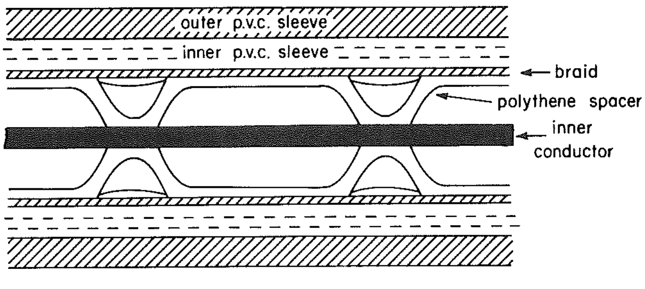

*Fig. 1 - Cross section through the leaky coaxial cable*

Outer diameter outer p.v.c. sleeve = 16·9 mm
Outer diameter inner p.v.c. sleeve = 13·1 mm
Outer diameter braid = 10·2 mms
Diameter inner conductor = 2·5 mms

Braid Parameters

Optical Coverage = 62% Lay length = 31·6 mms
Number of spindles = 24 Number of wires in each spindle = 4
Diameter of each wire = .18 mms

For maximum current transfer to the outside surface of the braid, the propagation velocities in the coaxial and single wire modes must be the same, the surface transfer impedance should be high and the attenuation coefficient for the single wire mode should be small.

Parameters for the sample of cable which was tested are given below.

Velocity ratio coaxial mode = 0·89
Velocity ratio single wire more = 0·89
Surface-transfer impedance at 27 MHz = 0·6 ohms/m
Attenuation in single wire mode
27 MHz = 0·178 dB/metre
85 MHz = 0·53 dB/metre
170 MHz = 1·07 dB/metre

No exact solution for the form of the surface wave has yet been derived. However, the solution is governed by certain constraints. Firstly, it must be symmetrical with respect to the central axis of the cable and secondly be consistent with a longitudinal current flowing on the outside of the braid.

Stratton[4] gives a general solution for Maxwell's equations assuming propagation along a cylindrical surface embedded in a dielectric. Applying these constraints to this solution, the only possible *single* mode is the Transverse Magnetic mode or Goubau mode. In cylindrical co-ordinates where the $x$-axis is the centre axis of the cylindrical surface the fields outside the surface are given by:[5]

$$E_x = B\, e^{j\omega t}\, e^{-\gamma x}\, H_0^{(1)}\,(jur)$$

$$E_r = B \frac{\gamma}{ju}\, e^{j\omega t}\, e^{-\gamma x}\, H_1^{(1)}\,(jur)$$

$$H_\theta = B \frac{\omega\epsilon_0}{u}\, e^{j\omega t}\, e^{-\gamma x}\, H_1^{(1)}\,(jur)$$

where $\gamma$ = propagation constant along the surface $r$ = radius from axis of cylindrical surface $u^2 = -(k^2 + \gamma^2)$, $k$ = propagation constant of free space and $H_0^{(1)}$ and $H_1^{(1)}$ are Hankel functions.

The solution is of the same form for cylindrical surfaces clad in a dielectric sheath as is the braid of the leaky coaxial cable. For most practical purposes, the Hankel functions can be expressed by an asymptotic approximation.

For this mode, the extent of the field outside the surface is governed by two factors.

(i) The higher the frequency the more the field is confined near the surface.

(ii) The higher the velocity of propagation along the surface, the greater the extent of the field outside the surface.

The velocity of propagation is controlled by the dielectric cladding the cable. The greater its thickness and dielectric constant the slower the velocity of propagation. For maximum field strength outside the cable (at any frequency) the following conditions should be achieved.

(i) High surface transfer impedance.

(ii) The velocity of propagation in coaxial and single wire transmission line modes to be the same, and as high as possible.

(iii) The dielectric cladding essential to protect the braid from damage should be of low loss material with a low dielectric constant.

## 3. Experimental work

### 3.1. Measurement of the attenuation of the cable in the coaxial mode

Using a vector voltmeter, the variation of attenuation of the cable with frequency for a correctly terminated 200 metre length was determined directly by measuring input and output voltages. In order to minimise any ground effects that might affect its loss the cable was supported ½ metre above the ground.

### 3.2. Measurement of velocity of propagation as single wire transmission line

Fig. 2 shows the experimental method employing a time domain reflectometer (TDR). The length of cable used was approximately 2 metres. The pulse from the TDR travels down the 50 ohm line, and some of its energy is coupled into the single wire transmission line mode of the test cable. The aluminium plate at the end of the 50 ohm line isolates the TDR from any unwanted reflections. The braid and inner conductor are joined at the driving point to prevent excitation of the coaxial mode. When the pulse reaches the reflecting plate some energy is reflected back to the TDR producing a 'blip' on the display. By moving the reflecting plate a known distance and recording the movement of the 'blip' on the time axis of the TDR display, the velocity of propagation can be calculated.

### 3.3. Measurement of the field strength pattern

Ideally, the field strength pattern should be measured for as great a length of cable as possible suspended high above the ground. However, practical considerations limited the length to 200 metres and the height above the ground to 3 metres. The cable was supported by 21 equally spaced wooden posts.

At the driving end, the cable was connected to a signal source situated on the ground beside the first post. The length of cable between the top of the first post and the signal source was about 10 metres. At the far end, the cable was correctly terminated in the coaxial mode, the termination being coincident with the top of the last post.

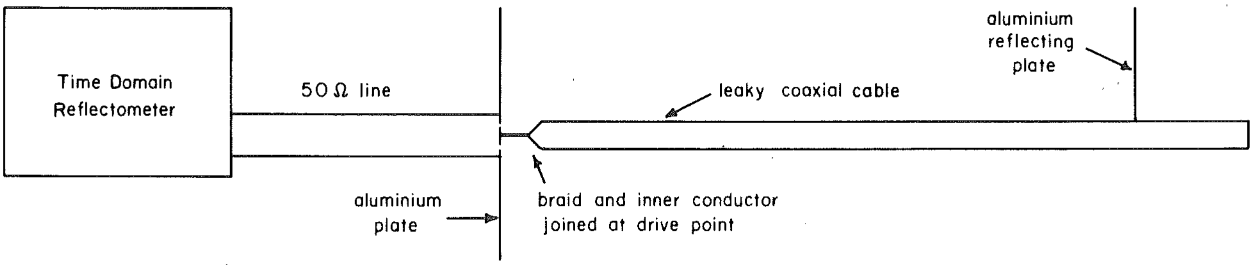
Time Domain Reflectometer
50 Ω line
leaky coaxial cable
aluminium reflecting plate
aluminium plate
braid and inner conductor joined at drive point

*Fig. 2 - Schematic of the system used to measure the propagation velocity of the outer braid as a single wire transmission line*

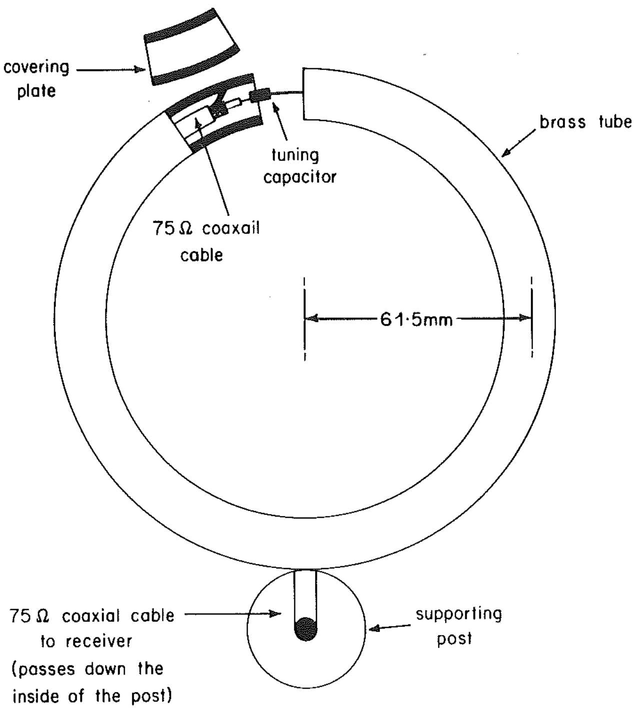

*Fig. 3 - View from above of the loop aerial*

In order to cope with the wide frequency range, a small single turn loop aerial was used. (See Fig. 3). The e.m.f. developed across the gap of such a loop is given by:

$$V = \mu_0 \pi r^2 \frac{dH}{dt}$$

$\mu_0$ = permeability of free space
$r$ = mean radius of loop
$H$ = magnetic field strength vector

This is true as long as $r < \lambda/20$. For the loop used, the radius equalled $\lambda/25$ at the highest frequency (196 MHz).

The output impedance of the aerial is a series inductance and a parallel capacity across the gap, the radiation resistance being negligible. From bridge measurements it was found that

the series inductance = 0·19 $\mu$H
and the parallel capacity = 1·5 pF.

The reactance of the loop was tuned out by a series capacitor at each frequency. A small allowance was made for the parallel capacity when calculating the gain of the aerial. The balanced-to-unbalanced transformation was achieved by running the cable inside the loop.

As a check, the aerial was tuned to 88 MHz and the gain compared with a standard dipole. The agreement between measured and calculated values was within 0·5 dB.

Ideally, the aerial should be as high as possible above the ground. A practical limit was found to be 2 metres, although in measurements made very close to the cable the aerial height was increased to 3 metres to make it level with the cable.

The downlead from the aerial was fed through a calibrated attenuator to the input of a portable v.h.f. receiver. The receiver was calibrated at each frequency against a standard signal source. By varying the attenuator setting so as to keep the input to the receiver constant, the field strength at any point could be determined.

## 4. Experimental results

### 4.1. Attenuation in the coaxial mode

Fig. 4 shows the variation of cable attenuation with frequency in the coaxial mode.

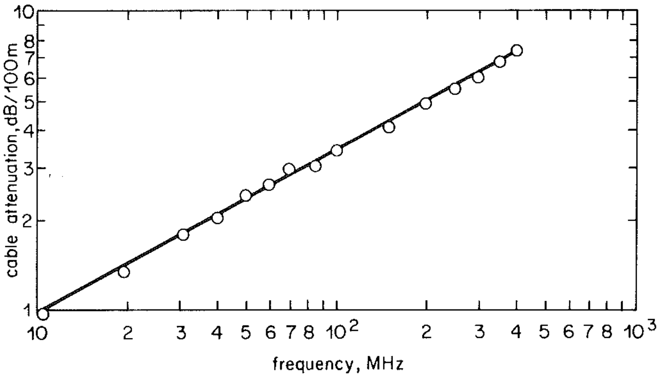

*Fig. 4 - Cable attenuation versus frequency*

### 4.2. Velocity of propagation as single wire transmission line

Velocity ratio with all p.v.c. sleeves on = 0·89
Velocity ratio with outer p.v.c. sleeve removed = 0·93
Velocity ratio with all p.v.c. sleeves removed = 1·0

The velocities as measured, were independent of the orientation of the cable with respect to the ground or its distance from the ground.

### 4.3. Field pattern

Figs. 5, 6 and 7 show field strength contour plots at three frequencies (40, 90 and 196 MHz) with respect to 1 watt at the input to the cable. Due to the presence of objects it was not possible to measure the field strength greater than 70 metres from the cable or greater than 40 metres off the end of the cable.

Measurements were hampered by the presence of an interference pattern. For any particular measurement position, moving the aerial only a small distance in *any* direction could change the signal into the receiver by up to 10 dB. The effect was most marked at distances greater than 25 metres from the cable, and at the higher frequencies. For any particular measurement position, the loop aerial was moved and rotated until the position of maximum

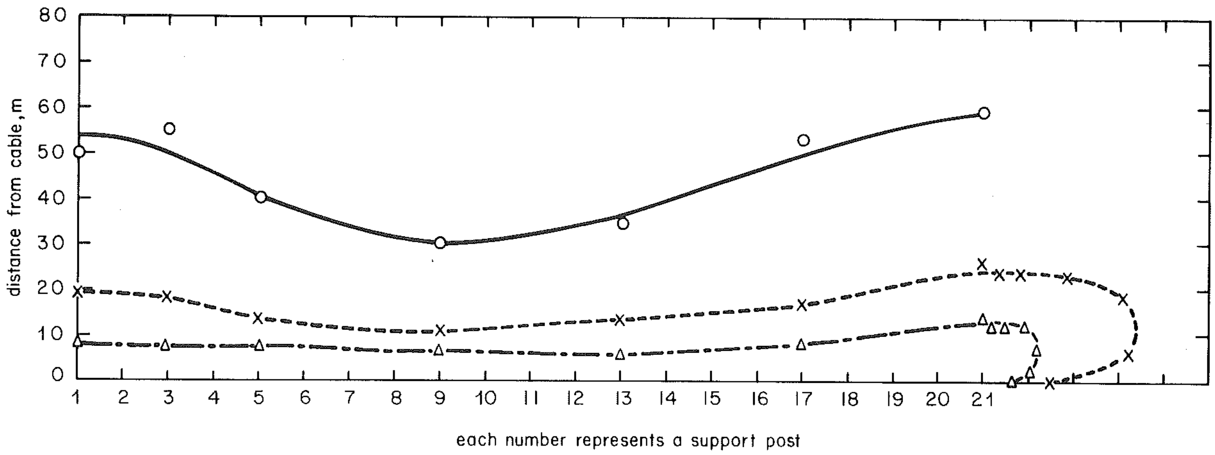

*Fig. 5 - Contour plot of the horizontally polarised field from the cable at 40 MHz, for 1 watt into the cable*

○——○ = 1 mV/m ×- - - - -× = 5 mV/m Δ——-—Δ = 10 mV/m

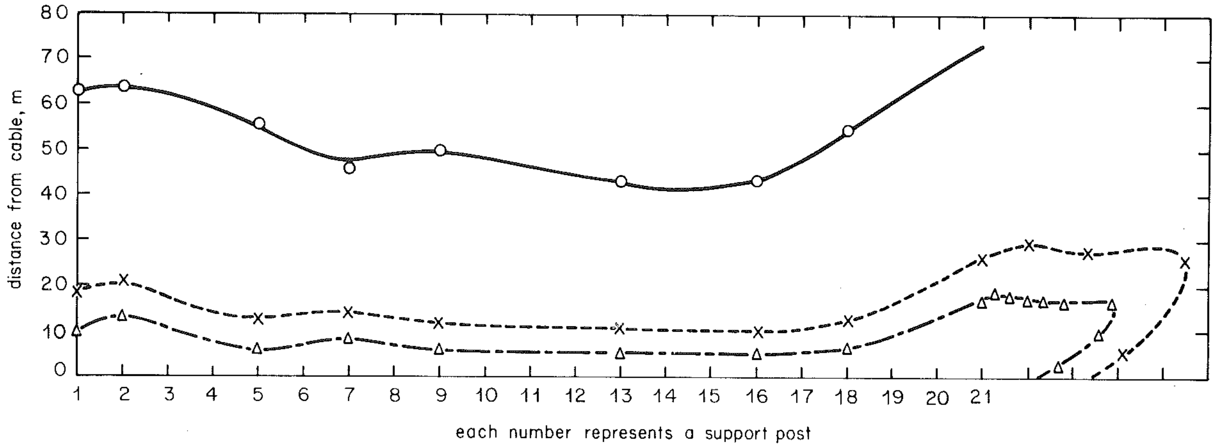

*Fig. 6 - Contour plot of the horizontally polarised field from the cable at 90 MHz, for 1 watt into the cable*

○——○ = 1 mV/m ×- - - - -× = 5 mV/m Δ——-—Δ = 10 mV/m

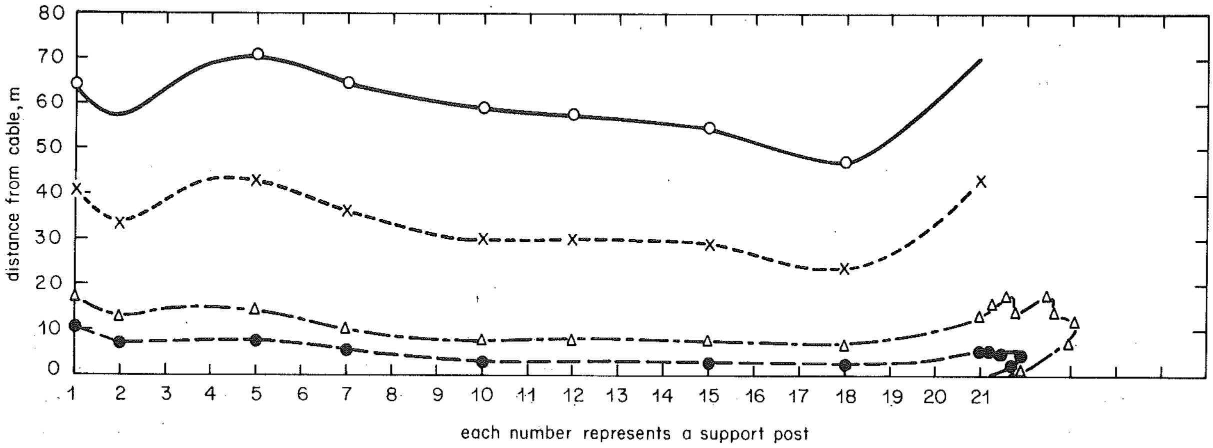

*Fig. 7 - Contour plot of the horizontally polarised field from the cable at 196 MHz, for 1 watt into the cable*

○——○ = 500 µV/m ×- - - - -× = 1 mV/m Δ- - - - -Δ = 5 mV/m ●— — —● = 10 mV/m

field strength was found. The contour plots shown are of these readings of maximum field strength.

Despite this precaution the accuracy of the results is limited in absolute terms and the contour plots should be taken as giving the form of the radiation pattern rather than the absolute level of field strength at each point.

Figs. 8 and 9 show the variation of relative field strength with distance from the cable at the centre of the elevated run for 90 and 196 MHz respectively.

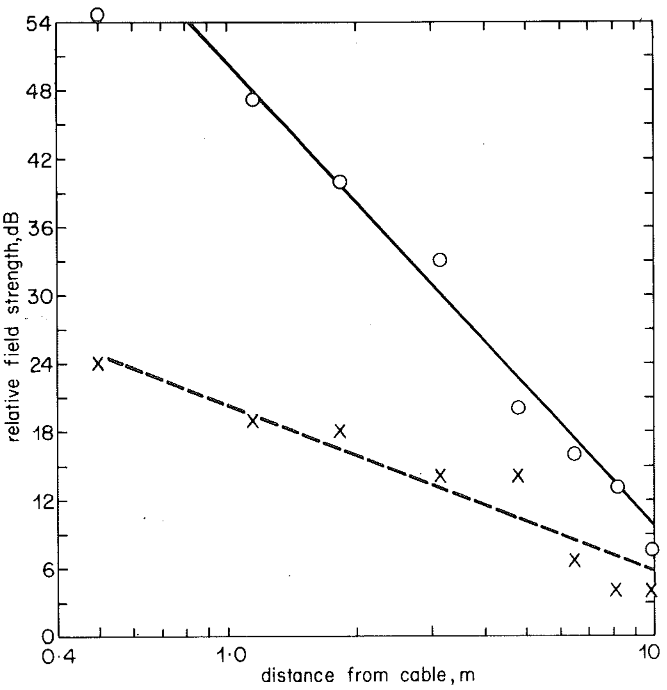

*Fig. 8 - Relative field strength versus distance from the cable at the centre*

Frequency = 90 MHz

O—O = horizontally polarised    X--X = vertically polarised

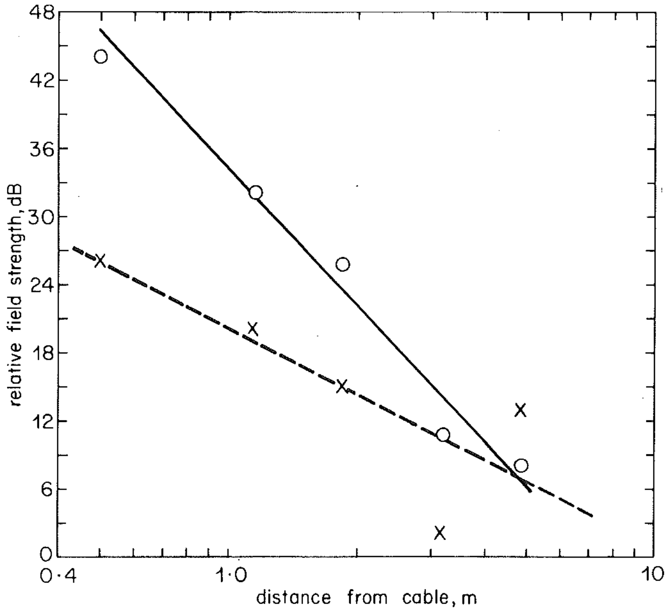

*Fig. 9 - Relative field strength versus distance from the cable at the centre*

Frequency = 196 MHz

O—O = horizontally polarised    X--X = vertically polarised

## 5. Discussion of experimental results

Assuming that the outside surface of the cable acts as a surface wave guide, then the field at any point outside the cable will consist of two components.

(1) The field from the surface wave assuming propagation along a perfectly straight cable with matched termination at each end of the cable. The field will be radially polarised and for points equidistant from the cable will decay longitudinally down the cable at the same rate as the field within the cable in the coaxial mode. No interference pattern except that due to the presence of the ground would be present.

(2) The field due to radiation from discontinuities along the cable which interrupt the surface wave. For the elevated run used in the experiment the main discontinuities are the ends of the cable. Some radiation will originate from the support posts, where the cable changes its direction. The curvature of the cable between the support posts will cause the surface wave to loose power continuously giving rise to what is known as a 'leaky wave'.

Since the discontinuities approximate to discrete sources, and their spacing is large compared to the signal wavelength, they will set up an interference field pattern with random polarisation.

From the contour plot, it can be seen that the increase in field strength at the ends of the cable is substantial. It is difficult to assess how much of this increase is produced by the increased braid current due to the reflected surface wave and how much is produced by radiation. The same difficulty applies to other discontinuities along the cable.

Whatever the cause of increased field strength at discontinuities, the result is an interference pattern superimposed on the field pattern produced by the surface wave.

From Figs. 8 and 9 it can be seen that the rate of decay of field strength with distance from the cable due to the surface wave is rapid, being approximately an inverse square law (close to the cable the surface-wave field predominates). The rate of decay of the field from the discontinuities represented by the vertically polarised field in Figs. 8 and 9 is much lower being approximately an inverse law. Hence at moderate distances from the cable the field from the discontinuities predominates and at more than 10 m variation of field strength with position is marked and could make it difficult to site a receiving signal so as to pick up sufficient signals in several channels.

To remove the discontinuities the cable would have to be perfectly straight and the supports would have to be electrically transparent. The ends of the cable would have to be terminated in the surface wave mode; at the frequencies used these terminations would be physically large. In any practical application envisaged for broadcasting it is unlikely that such ideals could be achieved. The variability of the field is less apparent close to the cable (less than 10 metres) where the surface wave field dominates. Close spacing from the cable is readily achievable in tunnels and mines and for this type of application, assuming that the communications receiver has an input signal dynamic range of about 70 dB, it should be possible to obtain a longitudinal range of 2 km at 100 MHz.

For broadcasting at about the same frequency, however, a relatively high minimum field strength is required and as an attenuation drop of 3·0 dB could be suffered over only 50 m of cable run high transmitter powers would be called for (up to 1 kW) with frequent power repeaters if the service was to be extended to a useful range. The introduction of repeater amplifiers into a leaky cable run would impose severe problems of stability and these would be worsened by the potential variability of the scattering environment.

Measurements of velocity of propagation of the surface wave show that it is dependent on the properties and thickness of the dielectric and is independent of the braid construction.

## 6. Conclusions

Leaky coaxial cables are at present being introduced as a means of providing v.h.f. communications in coal mines and there is a possibility that the technique could be extended in application for operations in other enclosed-area situations. Road tunnel broadcasting and radio talkback or radio microphones in television studios can be mentioned as examples. (At u.h.f. the leaky cable attenuation is too high for any application.) The investigation has shown that the leaky cable technique does not offer a means of v.h.f. broadcasting in the open owing to the severe technical difficulties which it presents. The principal drawbacks are:

(a) the need for relatively high 'transmitter' powers to put down the required level of field strength at the customers' aerials;

(b) the need to use frequent power repeaters with attendant stability problems if a useful range is to be covered and

(c) the impossibility of avoiding signal scattering for the cable supports and other objects.

As was shown in the tests, the effect of scattering is to produce a marked interference effect beyond about 10 metres from the cable run. The interference field exhibits frequency dependency which would lead to large field strength disparities between channels and to difficulties in siting receiving aerials satisfactorily. From the economic standpoint it must be concluded that the conventional type of cable run would be cheaper to install and maintain and would provide a superior service to the customer.

## 7. Acknowledgements

The authors express their grateful thanks to D.J.R. Martin for supplying the cable sample and useful technical information.

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# Appendix

## The Transfer of Current to the Outer Surface of a Braided Coaxial Cable

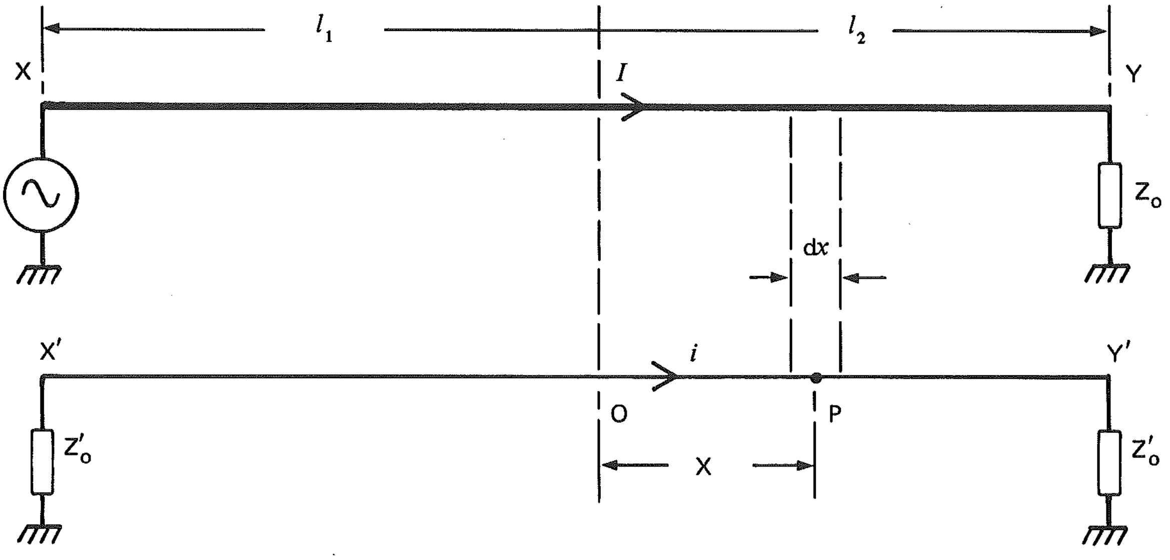

*Fig. 10*

In Fig. 10 XY represents a length of coaxial cable driven in its coaxial mode by a source at X and terminated by its characteristic impedance at Y. X′Y′ represents the outside braid surface of the cable which is assumed to be correctly terminated for the single-wire transmission line mode at X′ and Y′.

It is required to find the single-wire current at a point O, taken as the origin of co-ordinates, at distances $l_1$ from X and $l_2$ from Y.

Consider the element of cable d$x$ in Fig. 10. From the definition of the surface transfer impedance $Z_T$:

$$\frac{dv}{dx} = IZ_T \qquad (1)$$

where $^{dv}/_{dx}$ = voltage gradient on the outside surface of the braid and $I$ is the current on the inner conductor.

Rearranging:

$$di = \frac{Z_T}{Z'_o} I dx = KI dx \qquad (2)$$

where $i$ is the current on the braid and $Z'_o$ is the characteristic impedance of the outer braid surface = d$v$/d$i$, and $K = -Z_T/Z'_o$.

If the current at O in the coaxial mode is given by

$$I = I_o \cos\omega t \qquad (3)$$

then the corresponding current at distance X from O is

$$I_{(x)} = e^{-\alpha_1 x} I_o \cos\left(\omega t - \frac{2\pi}{\lambda_1}x\right) \qquad (4)$$

where $\alpha_1$ and $\lambda_1$ are the attenuation constant and signal wavelength of the cable in the coaxial mode respectively.

Whence, from Equation (2)

$$di(x) = KI_o e^{-\alpha_1 x} \cos\left(\omega t - \frac{2\pi}{\lambda_1}x\right) dx \qquad (5)$$

Assuming that this element of current propagates along the outside surface of the braid with velocity ratio $\rho_2$ and attenuation constant $\alpha_2$, then the current flowing on the outside of the braid at O due to the element d$x$ is given by

$$di = \tfrac{1}{2} KI_o e^{-\alpha_1 x} e^{+\alpha_2 x} \cos\left(\omega t - \frac{2\pi}{\lambda_1}x + \frac{2\pi}{\lambda_2}x\right) dx \quad (x<0) \qquad (6a)$$

and

$$di = \tfrac{1}{2} KI_o e^{-\alpha_1 x} e^{-\alpha_2 x} \cos\left(\omega t - \frac{2\pi}{\lambda_1}x - \frac{2\pi}{\lambda_2}x\right) dx \quad (x>0) \qquad (6b)$$

half the current from each element propagating in either direction.

The current $i$ is given by the summation of all such elements:

$$i = \tfrac{1}{2}KI_o \int_{-l_1}^{o} e^{(\alpha_2-\alpha_1)x} \cos\left(\omega t - 2\pi\frac{x(\lambda_2 - \lambda_1)}{\lambda_1\lambda_2}\right) dx$$
$$+ \tfrac{1}{2}KI_o \int_{o}^{l_2} e^{-(\alpha_1+\alpha_2)x} \cos\left(\omega t - 2\pi\frac{x(\lambda_1 + \lambda_2)}{\lambda_1\lambda_2}\right) dx \qquad (7)$$

$$= \frac{KI_o}{2}\left\{e^{ax}\,\frac{a\cos(\omega t - bx) - b\sin(\omega t - ax)}{a^2 + b^2}\right\}_{-l_1}^{o}$$
$$- \frac{KI_o}{2}\left\{e^{-a'x}\,\frac{a'\cos(\omega t - b'x) + b'\sin(\omega t - b'x)}{a'^2 + b'^2}\right\}_{o}^{l_2} \qquad (8)$$

where

$$a = \alpha_2 - \alpha_1$$

$$b = 2\pi\frac{\lambda_1 - \lambda_2}{\lambda_1\lambda_2}$$

$$a' = \alpha_1 + \alpha_2$$

$$b' = 2\pi\frac{\lambda_1 + \lambda_2}{\lambda_1\lambda_2}$$

If the line is long in both directions from 0 such that $l_1$ and $l_2 \to \infty$ then

$$i = \frac{KI_o}{2}\,(A\cos\omega t - B\sin\omega t) \qquad (9)$$

where

$$A = \frac{a}{a^2 + b^2} - \frac{a'}{(a')^2 + (b')^2}$$

and

$$B = \frac{b}{a^2 + b^2} + \frac{b'}{(a')^2 + (b')^2}$$

In order to produce Equation (9) in a simple form, it has been necessary to introduce other variables which are complicated functions of the parameters of the cable. This tends to make the equation difficult to interpret. However, it can be simply shown, that if all other things are kept equal, the current on the outside of the briad at O is a maximum when the velocity ratios in the single wire and coaxial modes are equal.

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